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(54) Increasing petroleum recovery

(57) A process for increasing the recovery of petroleum from a subterranean formation penetrated by a wellbore comprises the simultaneous stimulation of the producing formation from the wellbore by means of elastic waves, created by a vibrator installed in the wellbore so that the elastic waves which are superimposed reduce the adherence forces in the layer between oil/water and the rock formation, and the oscillating electrical stimulation of the same layer. The electricity heats the formation by means of resistive heating, and increases the pressure, thereby eliminating the surface tensions between the faces of the fluid as a consequence of the oscillatory actions of the ions in the surfaces of the fluid; in addition, it reduces the viscosity of the fluids. The process is achieved as the flow of petroleum produced in wells, thus treated, acts as a cooling agent which removes the heat released by the well area and thus allows a larger input of energy than in any other method known so far. The electrical energy is passed down the borehole to supply a well casing penetrating the formation and the vibrator.

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Fig.1
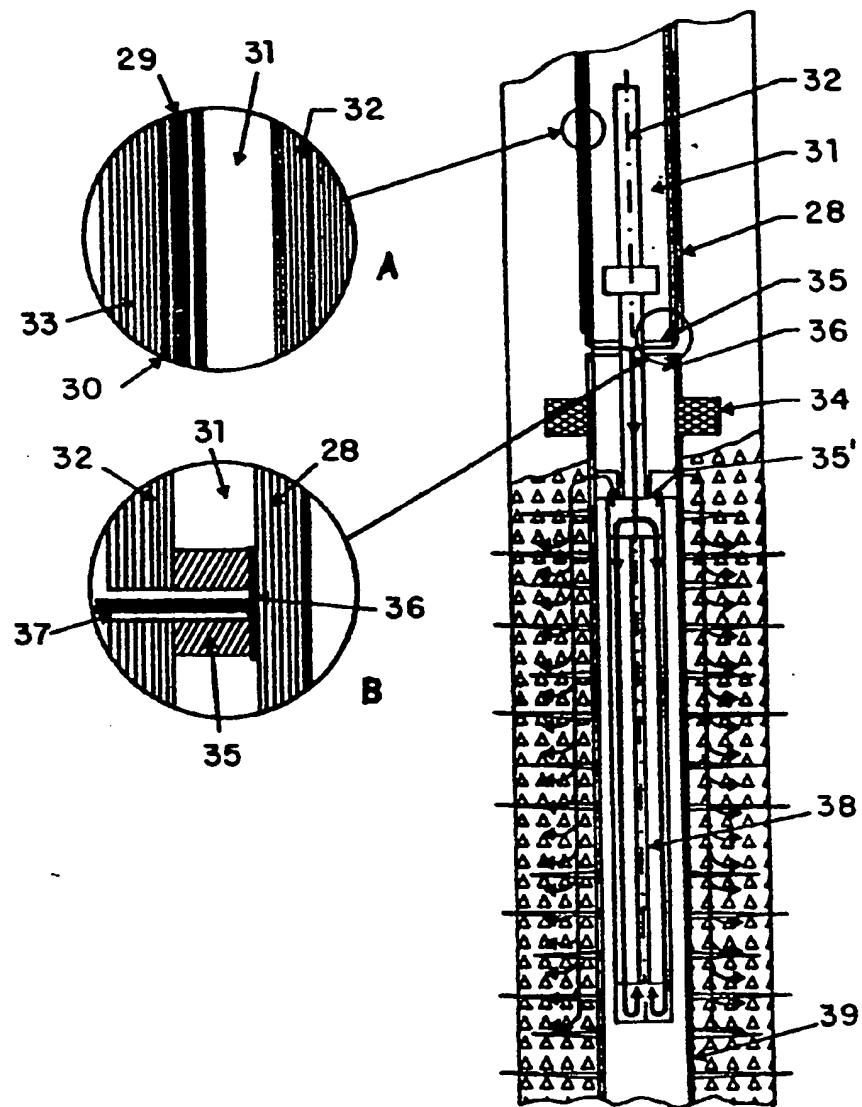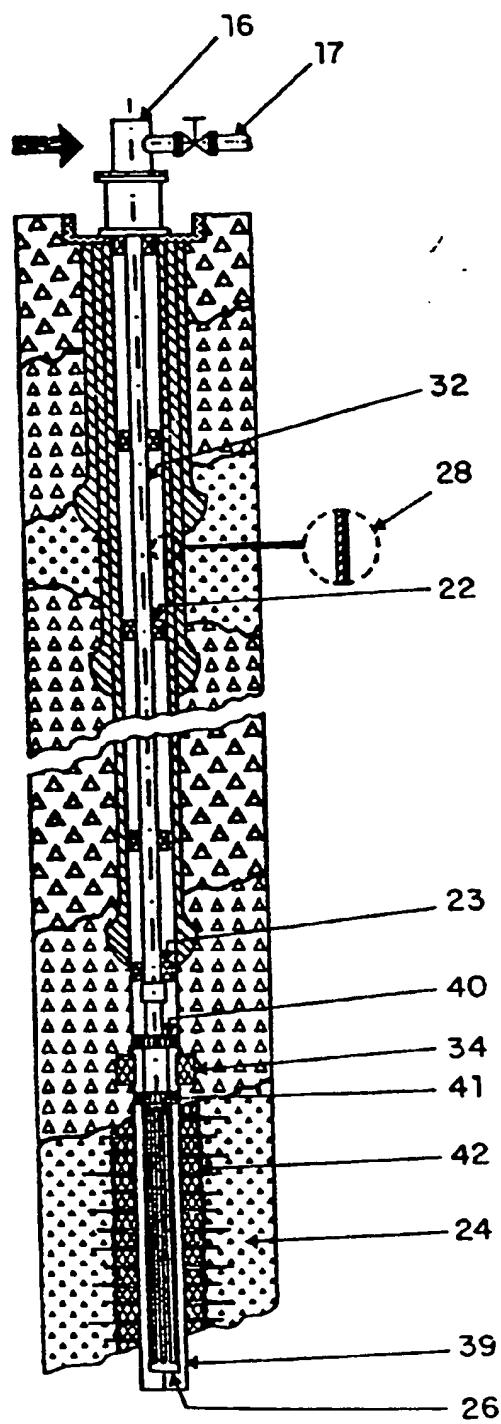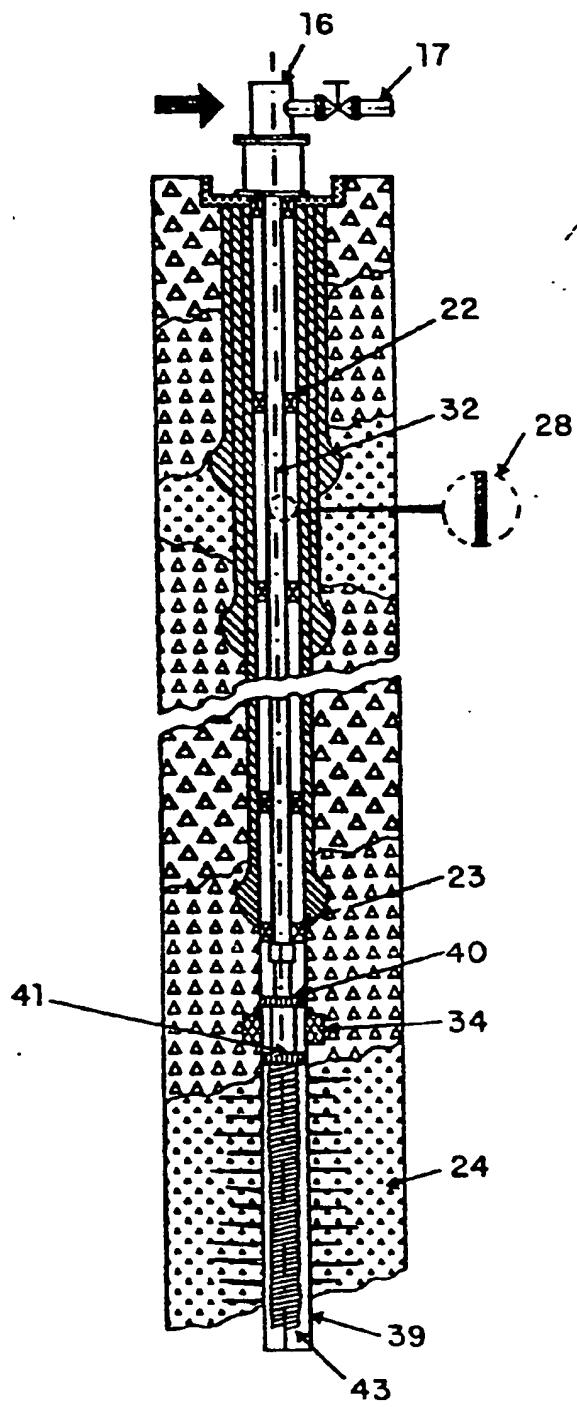
2/14

Fig.2

WELL 4

WELL 3

WELL 2

V + E | V | V + E |

V |

V + E |

Fig. 3

4114

Fig. 4

5114

Fig. 5

6114

Fig. 6
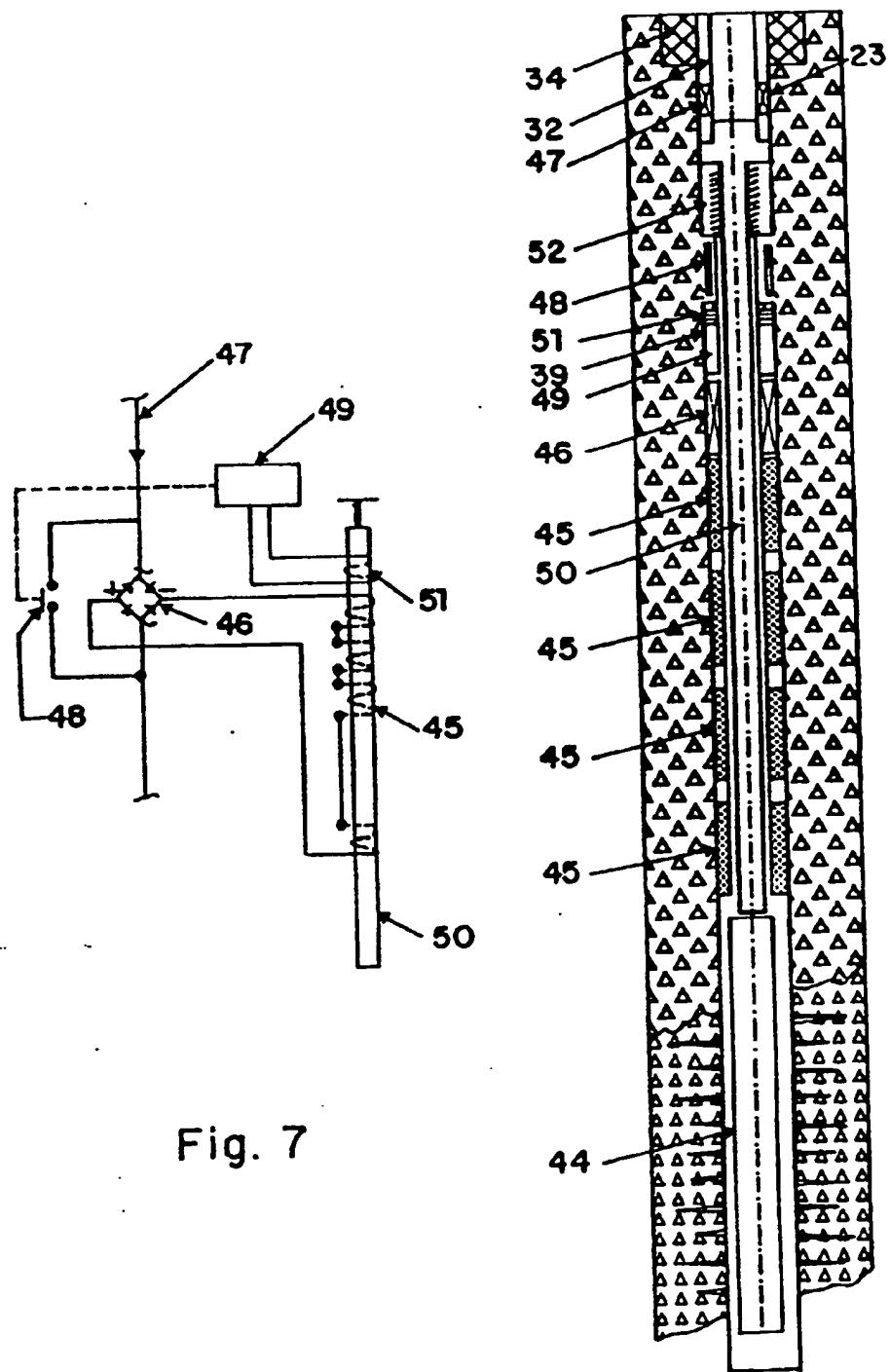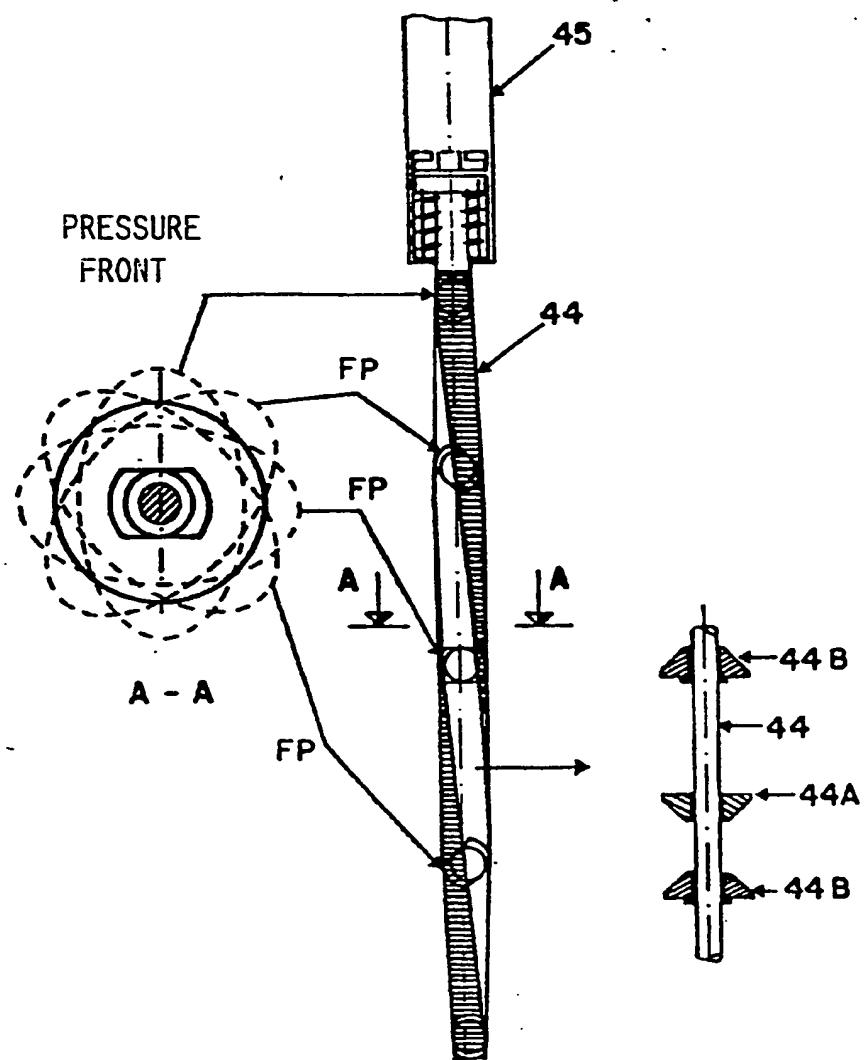
Fig. 7

8114

PRESSURE
FRONT

FP

FP

45

44

A ↓   A ↓

A

FP

A - A

FP

44 B

44

44A

44 B

Fig. 8

45

52

55

56

45

54

A

B

C

D

53
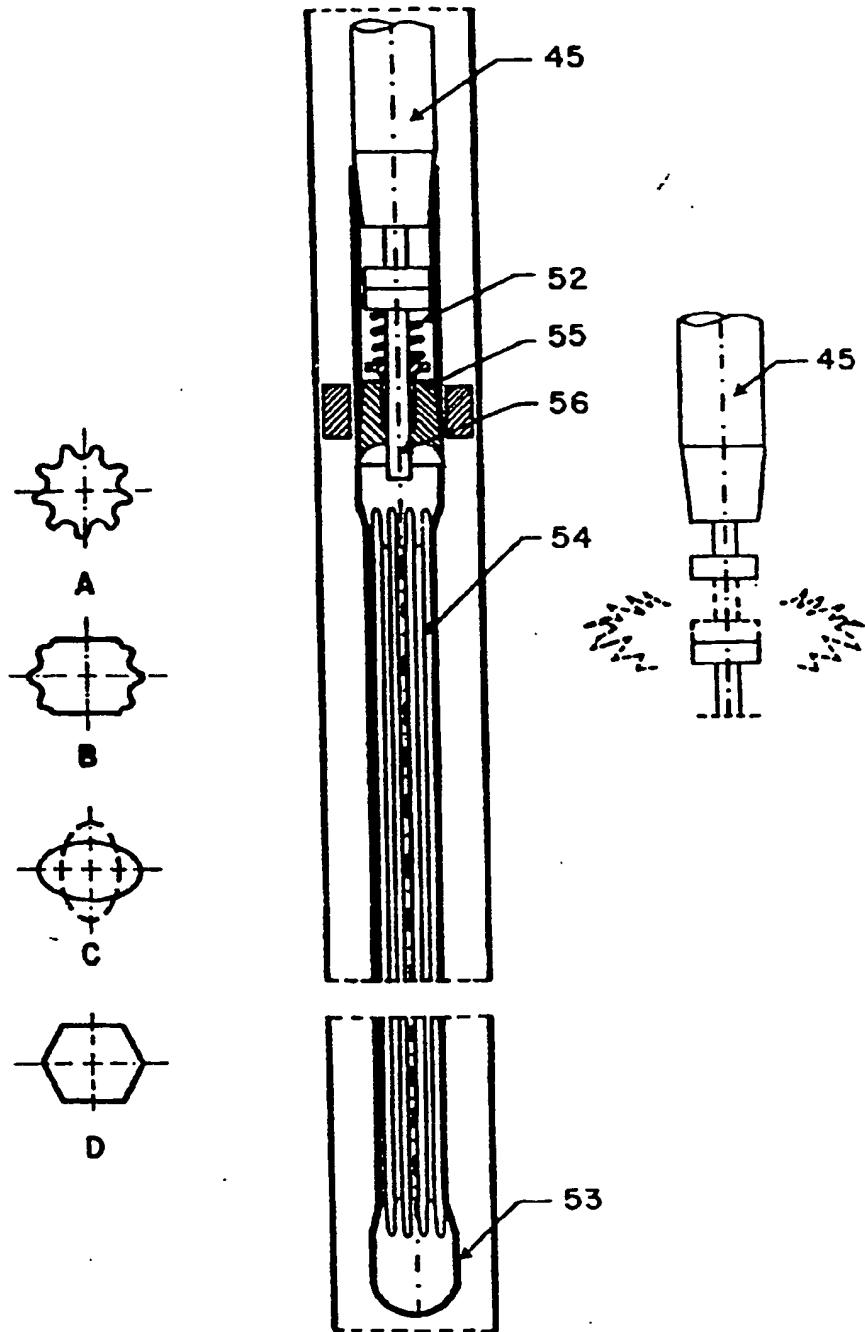
Fig. 9
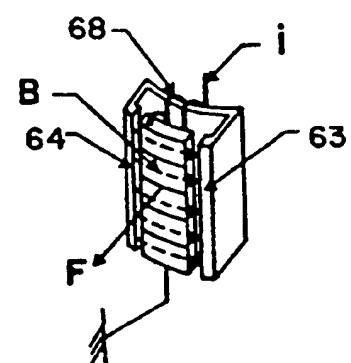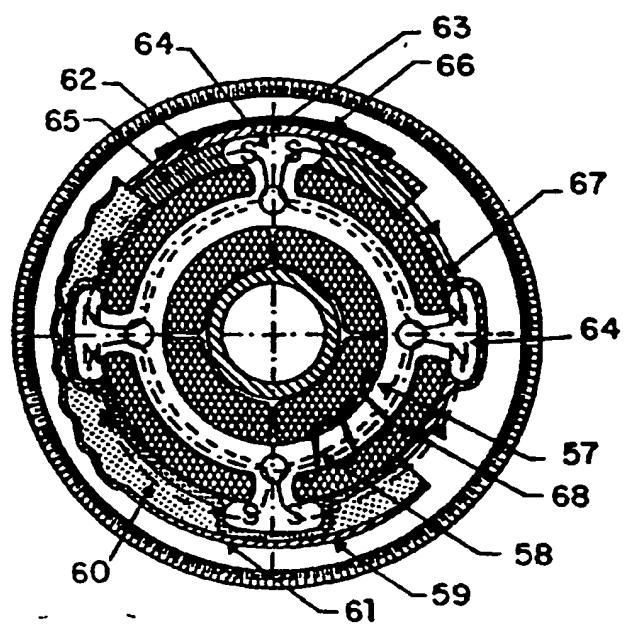
Fig. 10
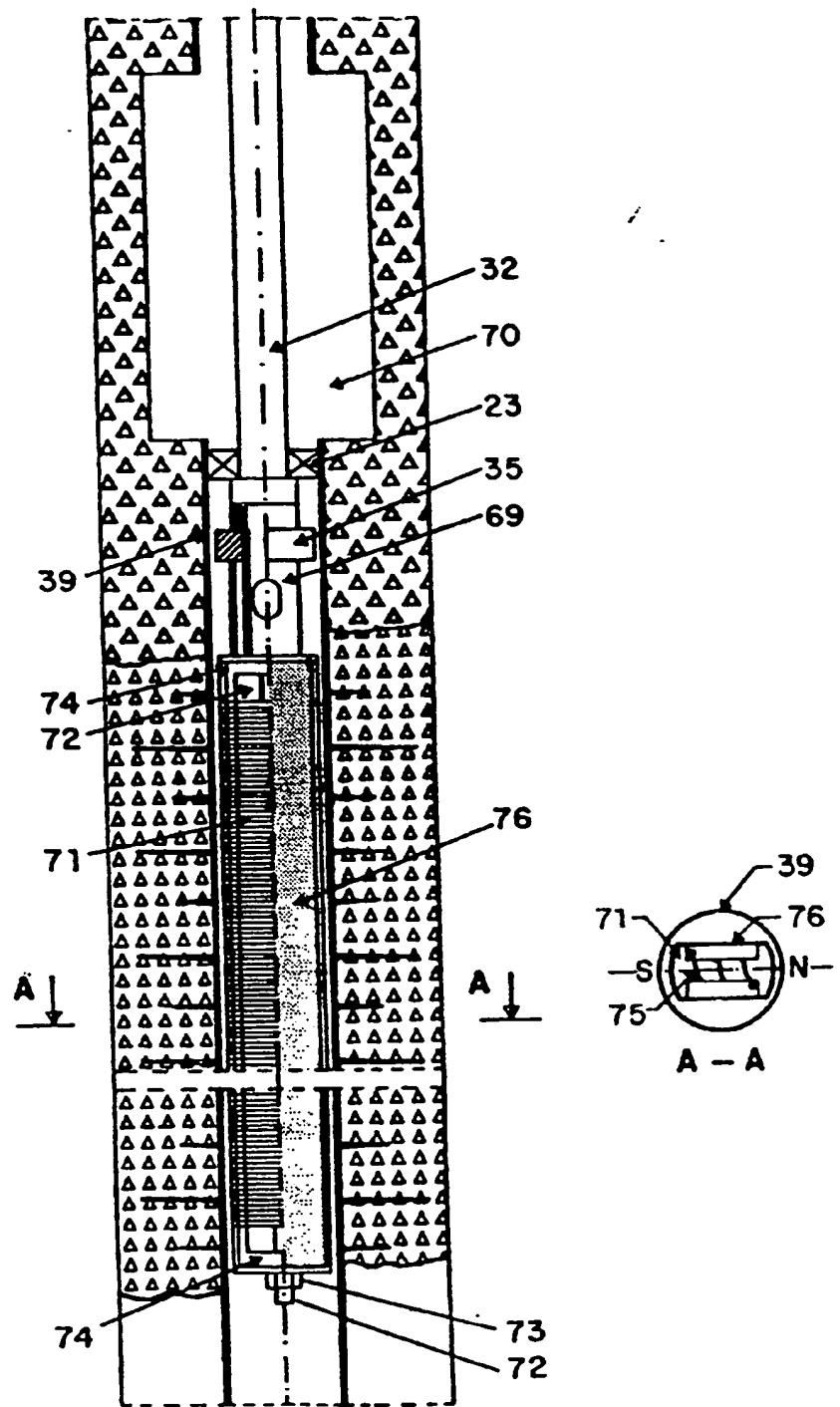
Fig.11
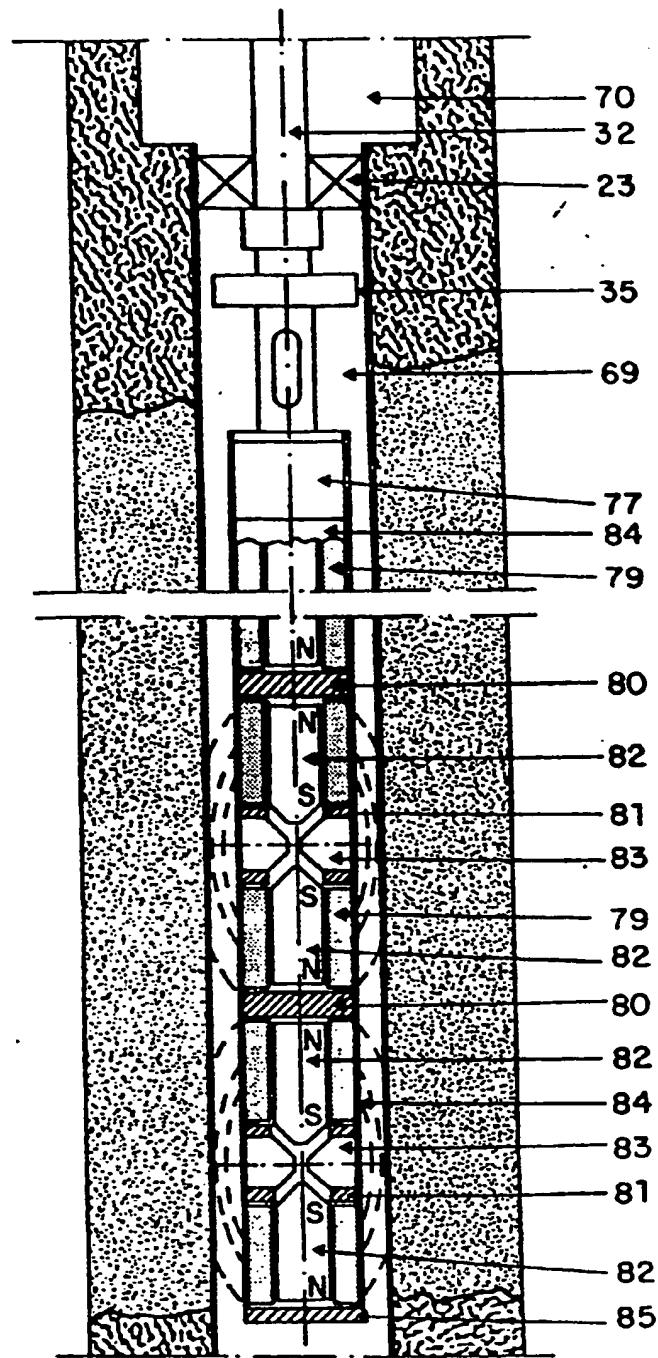
Fig. 12
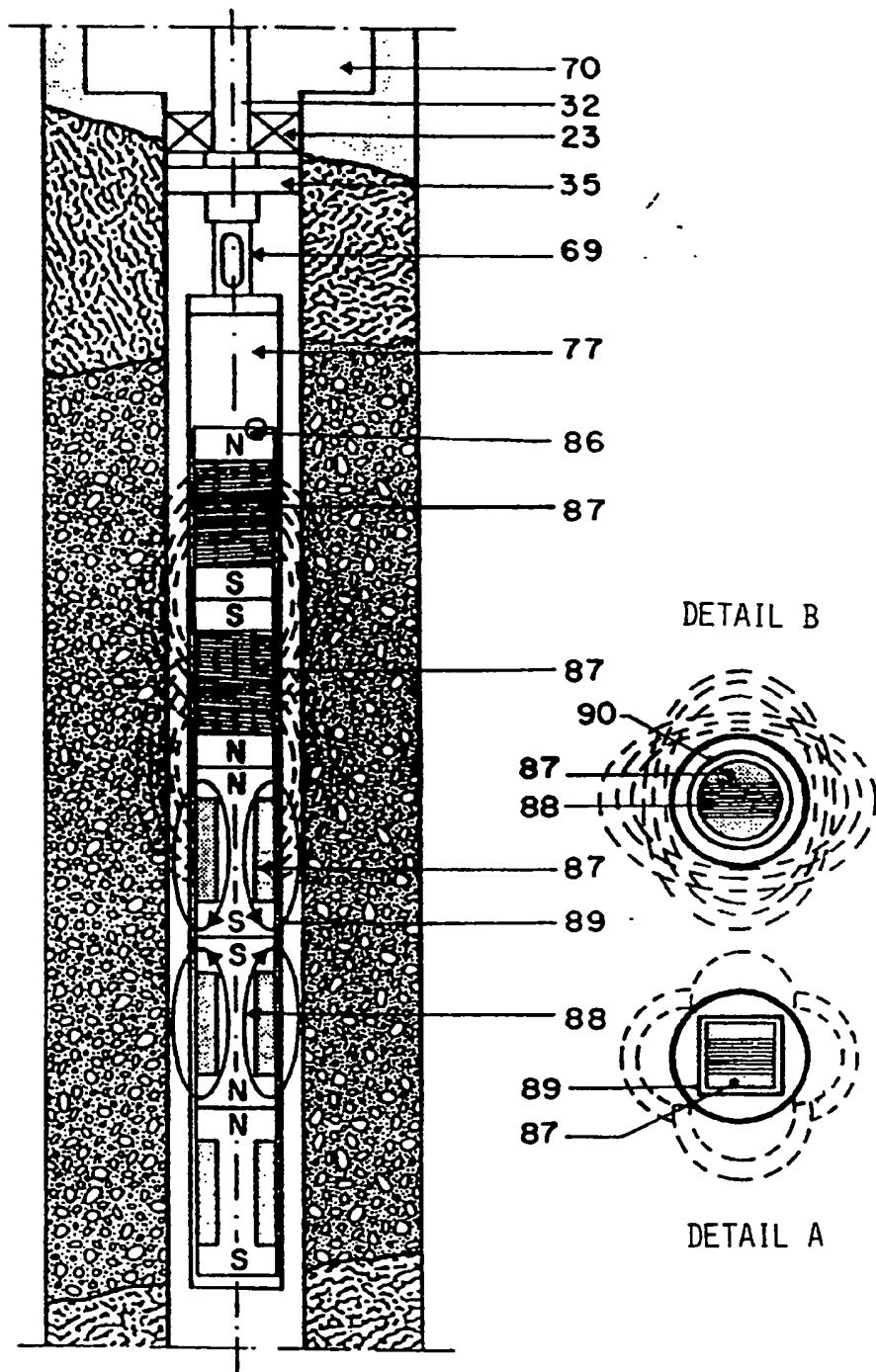
Fig. 13
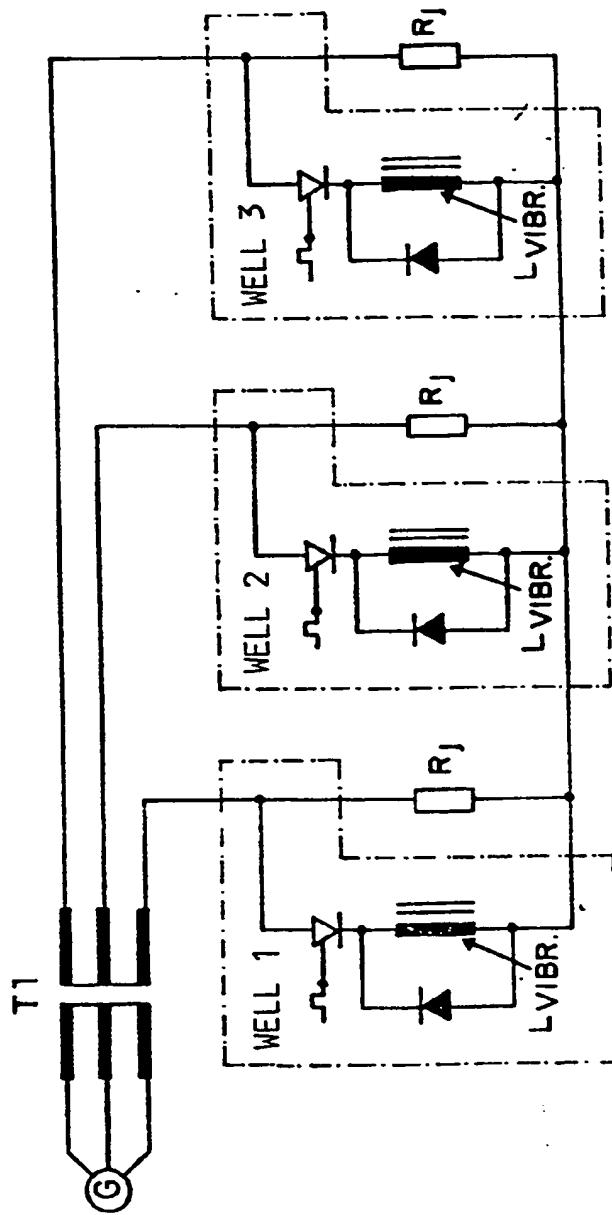
Fig. 14

."PROCESS AND APPARATUS FOR INCREASING PETROLEUM RECOVERY
FROM PETROLEUM RESERVOIRS"

This invention refers to an improved method for
5 petroleum recovery, by means of electrical and acoustic
stimulation of formation layers, as from the same petroleum
wells through which petroleum production is developed.

Hydrocarbons known as crude oil are found in
the world usually retained in sandstones of different
10 porosities. The reservoirs lay from a few meters to
several thousand meters below the earth surface and the
seabottom, and vary largely in size and complexity, with
respect to their fluid and gas contents, pressures and
temperatures.

15 Petroleum is produced by means of wells drilled
into the formations. The well itself is a complicated
construction, including casings which protect the well bore
against the formation itself and the pressures exerted by
the reservoir fluids. Depending upon the depth, the
20 casings are subject to a stepwise reduction in diameter.
In other words, pipe diameter decreases as depth increases.
It is not unusual to have 50" (127cm) casings in the upper
regions and 7.5" (19.05cm) casings in the lower ones.

Petroleum itself is drained from the productive
25 formation by means of holes drilled in the casing, being,
thereafter, lifted to the surface through what is referred
to as production tubing. This tubing is centralized inside
the casing by means of special centralizers, so that an
annular gap exists between the production tubing and the
30 casing.

Petroleum is initially produced due to the
original reservoir pressure being higher than the complex
forces of fluid adherence to the porous media. As pressure
decreases in the course of production, a point of
35 equilibrium is reached in which the adhesion forces are
higher than the remaining pressure. At this point most of
the petroleum is still in the reservoir. It is estimated,

as a global average, to be equal to nearly 85% of the
petroleum which was there initially, but the recovery
indexes vary largely from one reservoir to another. As an
example we mention the Ekofisk field, in the North Sea,
5   where the primary recovery index was 17% of the original
oil in place (OOIP), and the Statfjord, where said index is
estimated in 45% of OOIP.

The object of all methods designed to improve
petroleum recovery is, therefore, that of trying to
10   overcome those adherences. The theoretical base to explain
the cause of those adherences is as follows:

A - forces due to wettability

B - forces due to permeability

C - capillary forces

15   D - adhesive and cohesive forces

It is convenient that the adherence forces
dealt with in this invention be explained more in detail.

A - WETTABILITY
20   Wettability is one of the main parameters which
affect the location, the flow and the distribution of
reservoir fluids. The wettability of a reservoir affects
its capillary pressure, its relative permeability, its
behaviour under water injection, its dispersion, and its
25   electrical properties.

In an oil/water/rock system, wettability is a
measure of the affinity which the rock exhibits to oil or
to water. The wettability of reservoir rocks varies from
strongly waterwet to strongly oilwet. In case the rock
30   does not exhibit any strong affinity for either fluid its
wettability is said to be neutral or intermediate. Some
reservoirs exhibit a wettability which is heterogeneous or
localized, as a result of crude oil components which are
strongly absorbed in certain areas. Thus, part of the rock
35   becomes strongly oilwet, whereas the remainder may be
strongly waterwet. In other reservoirs what is referred to

·as mixed wettability may be found, since oil remains
localized in the largest (oilwet) pores, in the form of
continuous paths which pass by the rock, whereas water
remains restricted to the smallest (waterwet) pores.

5   Three methods are presently utilized to
quantitively measure the wettability: contact angle, Amott
method and USBM method. Through the contact angle one
measures the wettability of crude oil with brine in a
polished mineral surface. The method serves to verify the
10 effect on wettability of factors such as temperature,
pressure and chemical action.

          It is believed that most minerals present in
petroleum reservoirs, particularly silicates, are
originally waterwet. The arenitic reservoirs were
15 deposited in aqueous environments to which oil migrated
later. In the course of that process the wettability of
reservoir minerals may be altered by the adsorption of
polar compounds and/or deposits of organic matter
originally present in crude petroleum. The polar
20 extremities of those molecules may be adsorbed onto the
rock surface, forming a thin organic film, which in its
turn renders the surface oilwet. Depending upon the
temperature and pressure in the reservoir, those mechanisms
may alter the degree of wettability. Little research has
25 been conducted to investigate how a mechanical interference
can affect the wettability. The wettability of an
oil/water/rock system depends upon the adsorption and
desorption of polar compounds (electrical dipoles) in crude
petroleum on the mineral surface, which in its turn depends
30 upon the type of solubility of those compounds in the
reservoir fluid.

          To approach the problem of wettability one must
associate these electrical dipoles with the mechanical
stimulation so that the wettability is not allowed to
35 return to its original state.

B - PERMEABILITY

Permeability is the capacity of the porous rock to conduct fluids, that is, the property which characterizes the facility with which a fluid can flow
5 through a porous medium when subject to the influence of the application of a pressure gradient. Permeability is defined by Darcy's law, as a macroscopic property of the porous medium. Permeability is evidently related to the geometry of the porous structure, its porosity, tortuosity,
10 and distribution of pore size.

The concept of relative permeability is used in the situations in which two immiscible fluids, such as oil and water, flow simultaneously through a porous medium. Their permeabilities are independent of the flow rate and
15 of the fluid properties, and depend exclusively on the fluid saturations within the porous medium. The measurement of relative permeability is a critical factor in reservoir engineering, since it constitutes the predominant factor for the knowledge of flow properties in
20 a petroleum reservoir.

Controlling or improving the permeability is, then, a most important factor in improving the sweeping efficiency in displacements with water. It must be said that the displacement with polymers is the method most
25 utilized in mobility control. Water-soluble polymers are added to the water to be injected with the purpose of improving the mobility ratio, through the increase in viscosity and reduction of the permeability of the zones invaded, and, thus, prevent the water from breaking through
30 prematurely.

A great deal of research has been conducted for the purpose of creating polymers sufficiently inexpensive for this object, but with little success so far.

35 C - CAPILLARY FORCES

The equilibrium saturation in a petroleum

reservoir prior to initiating its production is controlled by rock geometry and by fluid characteristics. Since water and hydrocarbons are immiscible fluids, a pressure differential - the capillary pressure - exists between the
5   two fluid phases. If a wet fluid is displacing a non-wet fluid, the critical capillary pressure - depending upon pore size - must be overcome by the pressure differential in order to displace the wet fluid phase from those pores.

The ratio between (i) the pressure differential
10   applied (equivalent to the capillary pressure) and (ii) saturation characterizes the distribution of pore dimensions. The curve of critical capillary pressure verified for reservoir rocks serves to indicate the oil distribution in the reservoir and is, therefore, a major
15   parameter in the prediction of the oil saturation at different depths.

The capillary pressure is usually measured by the centrifugal method, through which a rock sample with original reservoir fluid saturations is immersed in the
20   wetting fluid and centrifuged at a series of selected angular velocities. For each velocity the average sample saturation is determined, and this, in its turn, is then correlated to the corresponding capillary pressure, by means of rather laborious numerical calculations (Hassler-
25   Brunner method).

Since the capillary pressure may oppose oil recovery, particularly in the case of small pores, it is most important to be able to control or reduce the capillary critical point in the tertiary oil recovery.
30   Chemical methods are usually employed, based on tensoactives, such as surfactants to reduce the interfacial tension. However, the results described in the literature show that the utilization of tensoactives has produced limited results due to the high cost of those products and
35   their large consumption by the reservoir rock.

D - ADHESIVE AND COHESIVE FORCES

The molecular forces which exist between two layers of different or similar substances are those which generate the adhesive or cohesive forces, respectively.

5   In the case of a fluid in porous rocks, adhesive forces exist between the fluid and the pore walls. Such forces appear particularly in the oil phase, as a consequence of the polar components in the hydrocarbons.

The adhesive forces are probably weaker than
10 the capillary forces mentioned above.

Since petroleum plays a preponderant role in the world economy, considerable efforts are being made to extend the production, in addition to the so-called primary recovery or natural reservoir depletion. Various methods
15 are known, discussed in the literature on the subject, as well as in ancient and recent patent documents.

The oldest technique, and for such reason the most well-known, has been that of injecting water or gas in what is usually referred to as injection well, aiming at
20 increasing the pressure and thus "squeezing" some more petroleum from the well. Other well-known techniques consist of different chemical and thermal methods, amongst which we mention the following examples extracted from the book, "Enhanced Oil Recovery, 1, Fundamentals and
25 Analyses", by E.C.Donaldson, G.V.Chillingarian, and F.Yen, ELSEVIER 1985.

Chemical Injection (alkalis) - This method requires a pre-washing to prepare the reservoir, and the injection of an alkaline solution or an alkaline polymer
30 solution, which generates surfactants in situ, to release the oil. Thereafter, a polymer solution to control the mobility, and a driving fluid (water), is applied, to displace the chemicals and the oil bank resulting from the process of recovery towards the production wells.

35 Carbon Dioxide Injection - This method is a miscible-displacement process which is adequate for many

reservoirs. The most feasible method is usually the utilization of a CO_2 bank, followed by alternating injections of water and CO_2 (WAG).

<u>Steam Injection</u> - The heat, from the steam
5   injected in a heavy-oil reservoir, renders this oil less viscous, thus displacing oil more easily through the formation, towards the production wells.

<u>Cyclic Steam Stimulation</u> - In this process, which usually precedes the continuous steam injection,
10 injection occurs in the producing wells at time intervals followed by well shutting-in, for heat dissipation and later return to production. These cycles are repeated until the production index becomes smaller than a minimum profitable level.

15   <u>In-Situ Combustion</u> - This process encompasses the ignition and controlled burning <u>in</u> <u>situ</u> of the formation oil, using the injection of pure oxygen or air as comburant. The heat released and the high-pressure gases make it easy to displace the heavy oils towards the
20 producing wells.

The textbook "Thermal Recovery", by Michael Prats, Monograph Volume 7, Henry L. Doherty Series 1986, deals with the technology involved in thermal recovery, the purpose of which is to heat the reservoir by different
25 methods. The book mentions also other applications of reservoir heating, and teaches how to utilize the formation heating around the well area, by means of electricity. Electrical current is conducted by means of an isolated
•   conduit, to a stainless steel screen at the bottom of the
30 well area. The current then flows out of the screen, passes by the oil at the bottom of the well, through the casing, and returns to a grounded conduit at the surface. In addition to problems of electrical connections at the bottom of the well, when the current flows through the
35 liquid, most of the energy is lost in the earth layers, even if its resistivity is lower than that of the

reservoir. This occurs because the current has to follow a distance hundreds of times longer in the earth layer.

Since those systems manage to deal with only part of the adhesion forces, large efforts have been made
5 to overcome the problem, thus improving the recovery by means of more elaborated methods.

For the present application and for the patents to which reference is made as follows, it is important to present a more detailed description of the adhesion forces.
10

Description of the Prior Art

In the patents presented as follows there have been attempts to solve the above mentioned problem. Same are relevant to the present invention, since they can be
15 seen as synthesis of the prior techniques.

US 2,670,801 (J.E. SHERBORNE) deals with the use of sonic or supersonic waves to increase the recovery and production of crude oil in petroleum formations. More precisely, it deals with the utilization of sonic and
20 ultrasonic vibrations, together with secondary recovery processes which utilize driving fluids, such as water injection, or gas injection, or similar, to improve the efficiency of the driving fluid utilized for the extraction of the petroleum remaining at the formation.
25 US 2,799,641 (THOMAS GORDON BELL) refers to promoting the oil flow from a well by electrolytical means. It describes a method to stimulate the well area with electricity only, but utilizing direct current, since the
• purpose of the invention is to increase the recovery
30 through the well-known phenomenon of electroosmosis.

US 3,141,099 (C.W. BRANDON) presents a device installed at the well bottom and is used to heat part of the well area by means of dielectric or arc heating. The only heating which may be achieved with this invention is
35 resistance heating. It is not possible to heat by means of arc since this would require electrodes arranged rather

close between each other, and then the arcs would melt the
rocks alongside them. As shall be seen later on, our
invention is much different, since it utilizes a method to
heat the reservoir, _in situ_, both electrically and with
5 vibrations.

US 3,169,577 (ERICH SARAPUU) refers to the
means to connect subsoil electrodes, between each other, by
means of electrical impulses, and relates precisely to
methods oriented towards inducing flow in producing wells.
10 The purpose is to drill additional wells, as well as to
create fissures or fractures near the well bore to
increase, thus, the drainage surface of the wells and heat
the hydrocarbons close to the well with the purpose of
reducing the viscosity of such hydrocarbons.

15 US 3,378,075 (BODINE) refers to a sonic
vibrator to be installed inside the well to subject it to
high-level sonic energy only, so as to achieve sonic
pumping in the well area. As a consequence of said high-
level sonic energy (and without the utilization of such
20 device associated to electrical stimulation), the effect of
muffling generated in the reservoir drastically reduces the
penetration of sonic energy. However, the method shows
improvement effects in the well area and contributes to
reducing hydraulic friction in the fluid flow. A similar
25 method is used in the former Soviet Union, aiming at
cleaning the pores in the well area, with good results.

US 3,507,330 (WILLIAM G. GILL) refers to a
method to stimulate the well area with electricity alone in
which electricity is passed "upwards and downwards" in the
30 wells themselves, by means of separate conduits.

US 3,754,598 (CARL C. HOLLOWAY, JR.) discloses
a method which includes the utilization of at least one
injection well, and another production well, to cause the
flow through the formation of a liquid to which oscillatory
35 pressure waves are superimposed from the injection side.

US 3,874,450 (KERN) refers to a method of

arranging electrodes, by means of an electrolyte, aiming at dispersing the electrical currents in a subsoil formation.

US 3,920,072 (KERN) presents a method of heating a petroleum formation by means of an electrical
5 current, and the equipment utilized for such purpose.

US 3,952,800 (BODINE) presents a sonic treatment for the surface of the petroleum well. The method, which is barely practical, intends to treat the well area by means of gas injection at the production well
10 itself, and to subject the gas to ultrasonic vibrations to heat the petroleum formations.

US 4,049,053 (SIDNEY T. FISHER ET AL) discloses different low-frequency vibrators for well installation, and which are hydraulically driven by surface equipment.
15 US 4,084,638 (CUTHBERT R. WHITING) deals with stimulation of a petroleum formation by means of high-voltage pulse currents, in two wells, one an injection well and another a production well. It explains also how to obtain such electrical pulsations.
20 US 4,345,650 (RICHARD H. WESLEY) presents a device for electrohydraulic recovery of crude petroleum by means of an explosive and sharp spark generated close to a subsoil petroleum formation.

Although the creation of hydraulic shocks by
25 means of a loaded capacitor is well known in the art, that invention presents an elegant vibrator as well as the advantages of utilizing shock waves to improve the recovery of petroleum.

US 4,437,518 (WILLIAMS) teaches how to use and
30 build a piezoelectric vibrator in a well, for petroleum recovery.

US 4,466,484 (KERMABON) presents a method to stimulate the well area by means of electricity alone, but by means of direct current, since the purpose of the
35 invention is to enhance the effect of electricity to recover petroleum through the well-known phenomenon of

electroosmosis.

US 4,471,838 (BODINE) describes another method to stimulate a well, with vibrations, which differs from the methods previously mentioned. Here are applied also

5 the teachings of patent US 4,437,518 (WILLIAMS). The major difference in this case is that the energy is generated by a source installed at the surface. Considering the large depth of wells in general, this method is barely feasible.

US 4,558,737 (KUZNETSOV ET AL) discloses a

10 bottom-hole thermoacoustic device, including a heater connected to a vibrating body. The intention is that the well area be heated and that the vibration of the heating device may activate the oil in that area, thus increasing the heat conductivity. It is a well-known phenomenon that

15 any agitation increases the heat conductivity in a given medium.

US 4,884,634 (OLAV ELLINGSEN) teaches a process to increase recovery, by making the formations in the petroleum reservoir vibrate as close as possible to their

20 natural frequency, so that the adhesive forces between the formations and petroleum can be reduced, and using electrical stimulation with electrodes installed in at least two adjacent wells. The process is achieved by filling a well with a metallic liquid to a height

25 corresponding to the formation height, vibrating said metallic liquid by means of vibrator already installed, and at the same time effecting an electrical stimulation through the application of an electrical current to said

• electrodes.

30 USSR 832,072 (GADIEV AND SIMKIN) deals also with a vibrating heater installed inside a well, by means of which the vibrations are intended to increase the heat conductivity.

USSR 1127642 and 1039581 disclose various

35 vibrators to be installed in a well to stimulate the well area alone.

CA 1096298 (MCFALL) discloses the construction of a resonator for fluids in which a fluid flow through and around a tubular or cylindric element, installed parallel to the fluid direction, generates in that flow vibrations

5 or vibration waves. This is only one additional way to generate waves in a well without the combination and techniques for simultaneous use of electrical stimulation. The resonator design is analogous to a whistle in which the rupture of air and its change in direction generate sound

10 waves.

The present invention relates to a process to recover petroleum from petroleum reservoirs, whether onshore or offshore, which includes the simultaneous stimulation of the formation by means of both vibrations

15 and electricity. The process is achieved applying special vibrations inside the layers, so that said vibrations be as nearly as possible equal to the natural frequency of the matrix rock and/or of the fluids existing there.

The present invention also concerns the

20 vibrators to achieve such process. Accordingly one aspect of the inventor provides a process for increasing the recovery of petroleum from petroleum reservoirs, wherein the producing formation is simultaneously subject to electrical and vibratory stimulation, in which the

25 electrical current is supplied to the reservoir by means of an electric conductor installed in an annular gap between a production string and a well casing; wherein part of the energy is utilized to operate a vibrator attached to the

• end of the production string, the electrical connection ⌐

30 being obtained by means of hydraulically driven connectors located at the vibrator and attached to the uncovered end of the electric cable; wherein said connectors conduct the electric current to the well casing which penetrates the producing formation at a point located above an isolation

35 bridge; wherein part of the well casing is located above the producing formation and there is a cut at a certain

height above said producing formation defining a cavity which is filled with an electrically insulating material.

An advantage of the method of the present invention is that the process acts on the whole reservoir, thus making it possible to increase its recovery factor and to reestablish production in wells where production is paralysed.

Another advantage of the present invention is that production can occur while the wells are being stimulated.

Another aspect of the present invention provides apparatus for increasing the recovery of petroleum from petroleum reservoirs, comprising a mechanical vibrator energized by current impulses supplied to the petroleum reservoir itself from the main power source; wherein said vibrator receives energy causing a displacement which can be oriented approximately at 90° and/or amplify the course of the original displacement by hitting different kinds of expansion devices which may make the casing oscillate in different ways in accordance with the acoustic characteristics of the reservoir.

Brief Description of the Drawings

In order that the present invention may more readily be understood the following description is given, merely by way of example, with reference to the accompanying drawings in which:-

Figure 1 shows a laboratory installation in which feasibility tests were conducted.

Figure 2 presents the results of tests in laboratory scale conducted using the installation shown in Figure 1.

Figure 3 shows a schematic arrangement of three wells equipped with vibrators, to achieve the process of the invention.

Figure 4 constitutes a view in detail of the

bottom-hole electrical circuit.

Figure 5 presents a well ready for application of the process of the invention, equipped with hydraulically driven vibrators and connectors.

5   Figure 6 presents a well ready for application of the process of the invention, equipped with a vibrator which works vertically.

Figure 7 presents in detail a vibrator of the invention, which works also vertically.

10   Figure 8 shows another option for the arrangement of the vibrator hammer.

Figure 9 shows one additional option for the arrangement of the vibrator hammer.

Figure 10 presents details of another vibrator.

15   Figures 11, 12 and 13 present also other options for vibrators.

Figure 14 presents a schematic diagram for obtaining low-frequency sounds.

20 Description of the Invention
The basic principle of the present invention is in the elements and devices utilized to obtain the advantage of stimulating the formation by combining simultaneous vibration and electric current flow.

25   This is achieved by introducing special vibrations in the formation layers. Those vibrations should be as close as possible to the natural frequency of the matrix rock and/or that of the fluids.

The confirmation of the above mentioned
30 principle was achieved by means of tests conducted in the laboratory, as shown in Figure 1, with the purpose of simulating on a laboratory scale the true conditions found in the formations. The tests were conducted as described below.

35   A sandstone block, with nearly 800mD of permeability and 22% of porosity, taken from an outcrop,

was isolated and saturated with water containing 40,000ppm of NaCl. Thereafter, the water was displaced with crude oil. The sandstone block was maintained at a temperature of about 38°C.

5   The porous medium 1 prepared as explained above was provided with three types of wells: namely production wells (2), an injection well (3), and observation wells (4) for temperature monitoring; and the laboratory rig was equipped with pressure sensors (5, 6), temperature probes
10 (12) and equipment (10, 11, 13, 15) for electrical stimulation and sonic stimulation means (9), as well as gas feeding means (7) and liquid feeding means (8) to the system.

        The tests were repeated several times utilizing
15 different arrangements of vibrators and electrical power supply, and with (i) the effect of the stimulation utilizing vibration alone, (ii) electricity alone, and (iii) vibration and electricity simultaneously. The oil recovered was collected in flasks (14).

20   It was verified that the vibrations generate various effects in the fluids retained in the formations:

        a)   they release the cohesive and adhesive links, as well as a large part of the capillary forces, thus allowing the hydrocarbons to flow through the
25 formation;

        b)   the vibrations which propagate inside the reservoir in the form of elastic waves modify the contact angle between the formation and the fluids, and reduce the coefficient of hydraulic friction. Thus, easier flow takes
30 place towards the wells, where a drastic increase in the velocity, as well as a larger pressure drop, occurs;

        c)   the elastic waves generate an oscillatory force in the layers, and, due to the different densities of the fluids, these accelerate differently. Due to the
35 different accelerations, the fluids "rub" each other and generate heat by friction, which in its turn reduces the

interfacial tension of the fluids.

In addition to these effects, the vibrations release the gas which was trapped, thus, which shall contributing to an expressive effect to increase oil
5   pressure.

In addition, the oscillatory force creates an oscillatory sonic pressure which contributes to the oil flow.

To maintain, and at the same time to increase,
10 the field pressure, heat is applied to the reservoir when the natural pressure has decreased. Heat is applied both in the form of frictional heat, caused by vibrations, and in the form of alternating current supplied to the wells. Due to the capacity of electrical current transmission,
15 always present in the reservoir, the current circulates in the wells and will make the reservoir act if it were an electric furnace, so that a resistive heating is consequently obtained.

The heating will cause partial evaporation of
20 water and of the lightest fraction of petroleum hydrocarbons.

The alternating current will make the ions in the fluids oscillate and thus create capillary waves in the surface of the fluids, thus reducing the interfacial
25 tensions.

The total heat generated both by the electrical stimulation and by the vibrations will reduce the viscosity of the fluids (ie. will render them thinner).

Both the vibrator and the electricity supply
30 menas are placed in petroleum producing wells and, thus, the oil which flows acts as a refrigerating medium, which allows the utilization of a large energy density.

These basic facts were verified by means of tests conducted on a laboratory scale and based on the
35 principle previously described. The results of one of those tests are represented in Figure 2.

The graph shows, as a function of time, the oil recovered from the production wells. The production of each well, the total production, and the type of stimulation applied during the tests, were traced, as

5   follows: V represents the vibrations only, E represents electricity only, and V + E represents vibrations together with electricity. After 80 hours the test was interrupted and later on restarted. Even so, the results were impressive.

10   The graph indicates that, with the process of the present invention, the recovery was 3.5 times greater than in the primary recovery. The results of the previous tests were nearly equal.

What is important to observe in this test is

15   that a drastic increase in oil production occurred with the stimulation by means of the simultaneous application of electrical and vibrational energy. Oil production occurred earlier than would be expected for the thermal effect by means only of pressure increase and drastic changes in

20   viscosity. This confirms the theory that the surface tension decreases with the oscillation of the ions in the fluids, which generates a fast increase in oil flow, together with acoustic stimulation, which accelerates the droplets.

25   It is necessary to explain better how the sound waves can affect petroleum production and what has been verified in our intensive laboratory research.

The movement mechanisms in a reservoir can be as follows:

30   1.   Fluid and matrix expansion.

2.   Water displacement.

3.   Gas displacement.

4.   Solution-gas displacement.

The process of this invention may be utilized

35   together with all those mechanisms, but its results are best in the case of solution-gas displacement.

In case of gas dissolved in oil, the gas
expands in the form of small droplets inside the oil as
pressure decreases, or as the reservoir is heated when
pressure is below saturation pressure.

5   The gas bubbles displace the oil, which flows
inside the reservoir following the pressure gradient. The
oil droplets are usually surrounded by water and very few
solid particles exist on which the bubbles can grow. In
this case an increase in the bubble point will occur in

10 accordance with the increase in the boiling point, and the
pressure in which the bubbles are formed will be
substantially lower than for a given temperature.
Therefore, it is necessary that the pressure be reduced for
the bubbles to be able to start growing on the microbubbles

15 which may be present in the liquid. It has been shown that
the acoustic vibrations interact with the increase in the
bubble point, so that boiling may more easily start.

      In addition, the surface tensions at the
interface between oil and gas shall prevent the oil from

20 flowing inside the reservoir. Those surface tensions at
the interface between oil and gas are relatively low and
decrease as temperature increases. Therefore, a very large
effect will be achieved with relatively weak vibrations.

      Our laboratory tests showed that, from the rock

25 matrix in which the flow stopped, it is possible to restart
the flow with a vibration as weak as 0.04g. With this a
recovery of up to 80% of the residual oil has already been
achieved.

      The explanation for that is that when the oil

30 flow stops it is because a point of equilibrium has been
reached, which can be altered by means of a weak acoustic
stimulation.

      As sound oscillations propagate in the radial
direction of the well, and oil flow in the same direction,

35 an optimum effect shall be achieved with the utilization of
a minimum amount of energy.

In addition it is known that oil, and other
fluids, flow more easily through a porous medium when said
medium is affected by vibrations, a fact which is
attributed to the reduction of hydraulic friction in the
5 pores. This explains why a liquid, considered as
Newtonian, acts as if it were a thixotropic fluid in small
droplets. In the limiting area between the liquid which
flows and the limits of the pores, the molecules shall
become "aligned" with some molecules in the thickness,
10 according to their higher or lower polarity.

If the liquid is subject to vibrations one
reaches what is referred to as capillary waves in the
fluid, and then the molecules will not have the time to
establish polar links. The thixotropic layer becomes
15 thinner and the oil will flow more easily. This phenomenon
interacts with the oscillatory movement of the ions in the
same surfaces, and will thus be superimposed on the
capillary waves created by the vibrations.

The energy in the sound wave which is absorbed
20 by the reservoir will be transformed into heat and will
therefore increase the gas pressure as a consequence of the
above mentioned partial evaporation, together with the
electrical stimulation.

It is a great advantage that the heat be
25 generated in the reservoir itself and that it does not have
to be transported to the layers, by conduction, or by means
of a heat-carrying medium, such as steam, hot water, or
equivalent.

At the time of water breakthrough in the
30 producing wells, it often happens that large quantities ·of
oil are retained in the reservoir due to the action of the
capillary forces. Oil recovery has already been achieved
in these conditions by means of sonic stimulation, but it
was necessary to utilize strong vibrations (5-10g).
35   The above mentioned US Patent 4,884,634,
prevents a system to achieve stimulation in a petroleum

reservoir by the simultaneous utilization of electrical and sonic means. It shows the main utilization of 3-phase electricity conducted into the wells with one or more vibrators immersed in a conducting liquid, such as mercury,

5 placed in the same wells. It has the advantage of making the conducting liquid oscillate as if it were a rope with several knots, so that the waves propagate into the reservoir as shells which expand and are superimposed on each other, creating a "hammering" effect inside the

10 layers.

However, this US patent does not deal with the details concerning the application of such a principle when the wells are old and when the equipment installed in them is of standard type.

15 This means that the process of the present invention is an innovation in the utilization of conventional production facilities and tools, and that the surface electrical system avails itself of usual equipment, such as commercially available transformers.

20 When trying to utilize the above principle in a reservoir, the following problems must be taken into account:

1. energy dissipation in the geological formations;

25 2. energy conduction to the vibrators;

3. control of total energy consumption;

.4. obtainment of electrical and acoustic connection with the well casing and of the well casing with the reservoir, so that the use of a conducting liquid may

30 be dispensed with; and

5. availability of a vibrator which is simple and durable, and which does not suffer from the instability usual in the vibrators already known.

One object of the present invention is to solve

35 the problems mentioned above, allowing the process to develop in a practical way and to be adaptable to

practically any type of reservoir.

Another object of the present invention is to
conduct the energy to the geological formations at the
bottom of the hole, with or without special electric
5 cables, as well as to utilize the energy to make the
vibrators work.

It is another object of the present invention
to interconnect the vibrator to the regular production
tubing, making the electrical connections operate with or
10 without hydraulic pressure in the tubing.

Still another object of the invention is to
allow the vibrator to be tuned at different frequencies and
transmit the so-called "pink sound".

One embodiment of the present invention
15 involves conducting the electrical current through an
electric cable installed in the annulus between the
production tubing and the casing. The electrical
connection is achieved by means of connectors, on a
separate connector assembly, and which are either installed
20 on the vibrator or connected to the uncovered end of the
electric cable.

An alternative embodiment consists of
conducting the electrical current through the production
tubing, centralized in the casing by means of special non-
25 conducting centralizers. In this option the annulus may be
filled with isolating oil to avoid any electrical
connection with the casing.

A further alternative embodiment consists of
conducting the electrical current through the isolated
30 casing, isolating the production tubing with the
centralizers.

As regards the vibrator it may receive energy
from the main feeding source. This energy will feed
initially the vibrators and then, through the connectors,
35 energy will pass to the casing, penetrating as far as the
petroleum formation, or vice versa.

The vibrators may also be fed from the main
feeding source, draining the energy from the main source to
the vibrator, at a chosen pulse. This means that the main
feed usually by-passes the vibrator, but is conducted to it
5 when it is activated. This can be controlled from the
surface or from the bottom of the hole by a discharge
device.

The electrical isolation which remains above
the petroleum formation may be achieved by cutting the
10 casing at a short distance above the petroleum formation
and filling the cavity with some type of isolating
material, for instance epoxy, isolating oil, or similar.
If desired, a fibreglass coating may be utilized above the
petroleum formation.

15   With the purpose of making it easier to
understand the invention, reference is made to Figures 3 to
14.

Figure 3 shows a general arrangement of three
wells equipped with their conventional elements, well-known
20 to the experts, such as wellhead 16 and flow lines 17 to
the oil tank. From a 3-phase power source, either a
generator or a transmission line, and starting from
transformers and control units 19 the feeding cables 18
extend towards the wells. A standard casing is aligned at
25 the well bore, the production string 20 being centralized
inside the casing by means of centralizers 22. At the end
of the string is a packer 23, known to the expert. The
casing is cut at a certain distance 25 above the producing
layer 24 to form a cavity which can be filled with
30 isolating epoxy or similar.

Below this point vibrators 26 remain suspended
from the production string 21. The current which flows
through the vibrators, or by-passes them, enters the part
of the casing which penetrates the petroleum layers, by
35 means of hydraulically driven connectors 27, or of a
mechanical connector made of a supporting device at the

bottom of the hole.

Figure 4 presents a typical view of the electrical circuit at the bottom of the hole.

The above mentioned power source may feed
5 alternatively the externally-isolated casing 28 or an electrical cable 29 provided with reinforcement 30.

When the current is conducted by means of the electrical cable, this cable remains in the annular gap 31, established between the production string 32 and the
10 internal wall 33 of the casing, as shown in detail A of Figure 4.

When the current is conducted by means of the externally-isolated casing 28, an electrical connector 35, which works hydraulically, remains attached to the string
15 32 and makes the contact directly in the non-isolated interior space 36, of the casing 28, located above the isolation bridge 34.

The current which leaves the conducting casing 28 through the conduit 37, or through the electrical cable
20 29, flows through the vibrator 38 and enters the lower casing 39 by another connector 35, which also works hydraulically.

Figure 5 shows a well, ready for the process of the invention, provided with an isolated casing 28 as
25 conducting element, and a vibrator 26 with hydraulically operating connectors 40, 41. In addition, the well bore is enlarged at the petroleum layers 24, as is well-known in the art, and the cavity 42 is either filled with salty
• concrete and drilled or with spheres in aluminium or
30 another metal, or else with another highly electrically · conductive material, such as a metallic or non-metallic conducting liquid, aiming always at increasing the area of the electrode and providing a good acoustic connection with the petroleum-bearing formation.

35 Figure 6 shows the same arrangement as Figure 5, except that the vibrator 43 oscillates vertically.

The main problem during the development of the
process of the invention consists of designing and
constructing vibrators which are reliable, inexpensive and
durable, and which can be synchronized at the natural
5   frequency of the petroleum-bearing formations, as defined
on page 187 in "RANDOM VIBRATION IN PERSPECTIVE", by Wayne
Tustin and Robert Mercado, of the Tustin Institute of
Techology, Santa Barbara, California.

            "NATURAL FREQUENCY, f_n - the frequency of the
10   free vibrations of a non-muffled system; also,
            the frequency of any type of the normal
            vibration modes. f_n decreases in case of
            muffling".

            Due to the muffling (attenuating) properties
15   which are always present in any reservoir, and which can be
evaluated by the Formation Quality Factor, it may be
verified, through the work presented by Yenturin A. Sh.,
Rakhumkulov R. Sh., Kharmanov N. F. (Bash NlPlneft't),
Neftyanoie Khkozvaistvo, 1986, No. 12, December, that the
20   effective natural frequency is in the range of from 0.5 to
5Hz, and that it can provide an acoustic pressure pulse of
2 to 20MPa, depending on the pressure prevailing in the
reservoir.

            However, we verify that this frequency can
25   reach nearly 100Hz, and, as an example, we may mention a
Brazilian petroleum field where the pressure is 16.7 bar
(1.67Mpa).   It has been verified in this case that the
optimum average sound pressure was 304KPa which results in
a pressure gradient of 108KPa and an acceleration of 5g in
30   the casing.   We have thus a vibrator with an average power
of 100kW = $18kW/m^2$.   At 5Hz this may generate a maximum
intensity peak of $362kW/m^2$ and a sound pressure of nearly
5MPa.

            The low frequency herein described generates
35   acoustic waves of deep penetration.   But, since it would be
advantageous to have available much higher frequencies

close to the well area, to achieve the effect of
emulsification and then to contribute to a lower hydraulic
friction, this question is solved by making the vibrator
transmit what is referred to as "pink sound", which means
5 noise containing many frequencies, which is incidentally
the case of most noises. For instance, recording the low-
frequency noise of given musical instruments, such as
drums, it can be verified that there is a number of
different frequencies at the upper part of the low-
10 frequency wave.

Since the effect of muffling in the reservoir
will absorb the low frequencies immediately around the
well, the object of the invention is automatically reached
by transmitting low-frequency "pink sounds". No method
15 known for stimulation with vibrations has already called
attention to this point.

In petroleum well logging operations a series
of vibrators is known which can transmit high powers at
various frequencies. None of such equipment, however, has
20 shown itself to be adequate to the purposes of the present
invention, since they have not been designed for continuous
utilization. In addition, they do not allow for the
associated use of electrical stimulation, nor can they be
fed from the main power source towards the wells.

25 Consequently, it was necessary to design
special electromechanical vibrators to meet the
requirements of the present invention. To reach this
purpose it was verified that it would be necessary to
convert electrical energy to magnetic energy, and this t6
30 kinetic energy in a body, and hence in a high-power
acoustic pulse. Such electromechanical vibrators are shown
in Figures 7 onwards, which will now be described as
follows.

Figure 7 shows a vibrator which works
35 vertically, and which includes a series of coils which,
upon being energized, drive a magnetised (armature) tube

within the coils, which transmits the thus-generated kinetic energy to a hammer 44 which alters the direction of the movement in elastic waves. This is achieved by means of the following elements: the coils 45 are connected in

5 series to a full-wave rectifier 46; the rectifier 46 is connected to the main supply conductor 47 which in the present case consists of the production tubing 32 and the lower part of the casing 39. Above the rectifier 46 is a general switch driven by a thyristor 48. This switch opens

10 at a given frequency by means of a time circuit 49. As the switch 48 opens, the direct current flow towards the coil, and the magnetic fields then generated in the coils, pull the tubular armature 50 downwards. A sensing coil 51 at the end of the path closes the switch again, and a spring

15 52, or the pressure inside the reservoir, will pull the tubular armature 50 upwards again. The oil flows through the tubular armature and carries away the heat generated in the coils.

There now follows a detailed description of the

20 hammer device 44 which receives the stroke of the tubular armature 50.

Figure 8 shows an alternative for the hammer device 44, which includes a bar 44 with V-shaped bodies 44A attached to the bar 44. At a certain distance below the

25 V-shaped bodies 44A are moving bodies 44B, the upper part of which is V-shaped. The bodies 44A, 44B may have different shapes and thus create different wave patterns as the bar is pressed into the liquid. The waves will be generated as the fluids between the moving bodies 44B and

30 the fixed body 44A are pressed radially outwards, since the high acceleration downwards of the bar causes the bodies to be pressed against each other at high speed. By placing the opposite sides of the bodies parallel to the bar 44, it is possible to make the casing bend axially as seen in

35 detail A-A. The great advantage of this is that deformation of the casing requires much less force than

when steel is drawn, as it occurs with the utilization of a
vibrator which sends force impulses in all directions at
the same time. By allowing the sides of the bodies to
follow a long helix, as seen in the drawing, it is possible
5 to make the casing oscillate as a musical instrument
string, thus transmitting pulses of superimposed waves into
the layers.

On the other hand, the tubular armature may hit
any construction which may change the direction of the
10 vertical movement of nearly 90°.

Another hammer device is shown in Figure 9.
The expansion element is in this case a flexible tube which
consists of an axially corrugated steel tube. The
downwardly pointing end of the expansion element is closed
15 by a cover 35. At the other end the tube 54 is connected
to a terminal part 55 where there is a piston 56. The
piston 56 can be pushed by the tubular armature 50 shown in
Figure 8, into the expansion tube 57, which is filled with
a liquid. The piston 56 is returned by means of the spring
20 52 or by any other elastic means. The expansion tube may
have any suitable cross-section, as seen in details A, B, C
and D, and all of these will generate different wave
patterns and allow the casing to bend axially as mentioned
above.

25 Another vibrator utilizes the vector product
between the electrical and magnetic flows, which results in
a perpendicular force F, which is the base for all
electrical motors, availing itself of the second electrical
current used for the wells. This alternative is disclosed
30 in accordance with Figure 10, where there is a core 57
built of rolled steel sheets, as in the armature of a
motor. In the core is a coil made of isolated copper wire
58, both the core and the windings being protected by
insulation 59. For the expansion element various options
35 exist, of which four alternatives are shown.

In a first option for the expansion element,

the expansion element is a corrugated tube 60 made of
stainless steel. The annular gap between the tube 60 and
the insulation 59 is filled with a liquid of high
electrical conductivity, for instance mercury. Instead of
5 utilizing a corrugated pipe, we may replace it by a
flexible hose 61 made of silicone rubber.

Another option for the expansion element is for
the tube 62 to be divided into four elements 63. In the
gap between adjacent poles 64 is an iron bar 65 attached to
10 the tube 62. The various tubes 62 are maintained united
by means of an elastic silicone hose 66.

Still another option is a corrugated tube 67 of
special format.

The operation of the vibrator is as follows.
15 The current i from the conductor of the well
passes first through the coil 68 and thus generates a
magnetic flux B between the poles 63, 64. Thereafter the
current passes through the expansion element (in the first
two options constituted by the conducting liquid), and then
20 into the petroleum-bearing formation. The circuit is
arranged so that the force F may act against the casing and
the producing formation. As the direction of the current
and of the magnetic field changes, due to the alternating
current frequency, the frequency of the vibrations will
25 duplicate. That is to say if the current is at 50Hz
frequency, the frequency of the vibrations will be 100Hz.

In some reservoirs this may be the optimum
frequency, and therefore it will not be necessary to
• manoeuvre the force to the vibrator. But if it should not
30 be advantageous to utilize a lower frequency, the force may
be fed as described for Figure 7, or by transmitting a
high-voltage pulse from the surface, which makes the
current pass through the coil in the vibrator and hence
into the producing formation. This force may be fed also
35 from a charged capacitor, or from a coil as in the ignition
system of a car.

Figure 11 shows another option for a vibrator.

The coupling scheme 69 shows the hydraulically operated connector 35 attached to the end of the production string 32 with its insulated packer 23 below the enlarged area 70. The vibrators can also be seen, in the form of a core 71 composed of iron sheets united by means of a bolt 72 and a nut 73. At each end of the core are two terminal parts 74 which press on the bundle of rolled iron sheets forming the core 71. Around the core is wound a coil 75 of copper wire which, upon being energized, generates a magnetic field with north and south poles at each side of the core, as seen in the section A-A of Figure 11. In order to protect them, the coil and the core are placed inside a non-magnetic tube 69 having the section shown. The spacing between the core/production tubing set 76 and the steel casing is nearly 1mm.

The operation of this vibrator is as follows: as the current passes through the coil 75 and then through the connector 35, and into the formation, an oscillating magnetic flow B is generated in the coil, which changes in direction in accordance with the alternation frequency of the current. Since the oscillating magnetic flux will attract the casing in the same direction, it will vibrate at twice the frequency of the power source, according to detail A-A, due to the electricity of the steel. This results in the same advantages pointed out in relation to the movement of the casing dealt with above, for the expansion element of the vertical vibrator shown in Figure 7.

For the case of large thicknesses of the producing formation, the core of Figure 11 may be twisted and it shall be thus possible to make the casing vibrate, transmitting wave trains from the casing, and to superimpose the knots.

Should it be required to utilize a frequency lower than the alternation frequency of the electric

current, this may be obtained in the same way as that
described for the vibrator of Figure 7, which energizes the
coil with high current pulses. It is also convenient to
point out that all the shocks generated by the vertical
5 vibrator automatically generate pink sounds. To achieve
these pink sounds in the vibrators which transmit
horizontal shock waves, and which vibrate at twice the
frequency of the power source, a frequency modulator is
used. In its simplest form this may be done with a tape
10 recorder whose signal is amplified by a transformer. We
may verify that it is thus possible to utilize special
"music" for frequency modulation.

     In the case of the vibrator which operates in
accordance with the principle described in Figure 11, it
15 may be advantageous to build it with a special expansion
element which vibrates instead of the casing. This is
achieved by installing the coil assembly set 72 inside an
additional flexible tube which may be caused to vibrate.
The cross-section of this expansion tube may be circular or
20 elliptical.

     Figure 12 shows still another vibrator. The
coupling scheme 69 shows the hydraulically operated
connector 35 attached to the end of the production string
32 with its insulated packer 23 below the enlarged area 70.
25 Below the coupling 69 is a void space 77 intended for the
switches which control the vibrator 78. The vibrator
consists of a series of coils 79 attached to each other by
means of spacers 80 and tube sections 81. In the central
holes of the coils, for each pair of coils, there are two
30 iron pistons 82, with their ends which face each other
chamfered in parallel at a 45° angle. The coils are wound
so that for each pair of adjacent pistons, the magnetic
poles which face each other remain of opposite polarity.
The plane end of each piston 82, which faces the piston of
35 the other pair of coils, has the same magnetic pole as it
does. A hole is drilled in the sections of pipe 81, in

which two small pistons 83 are placed in opposite
direction, and the end turned to each other is cut in
parallel at a 45˚ angle. The various coils with their
pistons are placed in a steel tube 84 which is closed at
5 the bottom by a plate 85.

The function of the vibrator is to transmit an
electrical current into the coils, which will generate
magnetic fields and the above mentioned magnetic
polarities. The pistons 82 attract to each other and press
10 the small pistons 83 radially outwards. The vertical
movement of the pistons 82 and, therefore, the kinetic
energy absorbed as they reach the pistons 83, will be
transformed into acoustic energy as the steel tube 84 is
bent. Without using an expansion pipe 84 the power would
15 be transmitted from the radial pistons 83 as a burst.

Each end of the pistons 83 will transmit
elastic waves of high power and low frequency. Even though
the magnetic field increases slowly, the sudden impact on
the ends of the piston 83 will make possible the generation
20 of pulses of several kW.

These statements are supported by the following
equations.

For calculation purposes, the magnetic flux
density in the air gap between the poleshoes is assumed
25 homogeneous. Also, the residual magnetic field in the
ferrous material, the current induced by the frequency
fluctuation in the magnetic field, and the magnetic losses
in other parts of the circuit are assumed negligible.

The Ampère Law shows that:

30 $$\oint H \, dl = I$$

where: H = magnetic field strength
       l = circuit length
       I = electric current

The magnetic force may be expressed as:

35

$$F = \frac{dw}{dx} \quad \frac{1}{2} \quad \frac{B^2}{\mu} \quad . \quad A \qquad (1)$$

where: F = magnetic force

W = magnetic power

X = field displacement

B = magnetic flux density

A = transversal area of the
   magnetic circuit

μ = magnetic permeability

Then, the magnetic field is:

$$\oint H \, dl = I_{total}$$

$$\oint H_{Fe} \, dl + 2 H_{air} \, \delta = NI$$

where: δ = size of the air gap

N = number windings in the coil

Assuming $H_{Fe} = 0$, we will have $2 H_{air} \, \delta = NI$ (2)

Thus:

$$H_{air} = \frac{1}{2} \quad \frac{NI}{\delta} \quad \text{and} \quad B_{air} \, \frac{1}{2} \quad \frac{NI}{\delta} \, \mu_0 \quad (3)$$

Combining equation (3) into equation (1):

$$F = \frac{1}{2} \quad \frac{B^2}{\mu} \quad . \quad A = \frac{\mu_0}{8} \left(\frac{NI}{\delta} \right)^2 . A \quad (4)$$

This equation shows that the magnetic force increases parabolically, as an inverse function of the air gap size. This indicates that the force will dramatically grow until the instant of impact.

Considering, for project purposes based on Figure 12, the following values

$A = 0.02 \, m^2$; $N = 1000$; $I = 5$ Amperes ; $\delta_{max} = 0.01mm$; $m = 5kg$, the magnetic force corresponding to each position of the piston and the accumulated power at the end of piston travel, can be calculated. The results are shown in Table I.

δ_x [m]	$F = \mu_0 \dfrac{NI}{8\,\delta}{}^2 \cdot A$ [N]	$a = \dfrac{F}{m}$ [m/s²]	$v = v_0 + \sqrt{2as}$ veloc. at δ_x [m/s]	$E = \dfrac{1}{2}\,mv^2$ [kW]
0.0100	785	157	0.18	0.08
0.0090	970	194	0.38	0.36
0.0080	1300	260	0.61	0.93
0.0070	1600	320	0.86	1.85
0.0060	2180	436	1.16	3.36
0.0050	3140	628	1.51	5.70
0.0040	4900	980	1.95	9.50
0.0030	8700	1740	2.54	16.13
0.0020	19600	3920	3.43	29.41
0.0010	78500	15700	5.20	67.60
0.0005	314000	62800	8.75	191.18

At the impact point ($\delta = 0$), the power should
be infinite. However, a realistic value can be estimated
as 100 Joules and the time for dissipating this energy
0.001 second, Thus, the power per plunger will be:

$$W = \frac{100}{0.001} = 100 \text{ kW}$$

Each train of waves of the small pistons 83
will be superimposed on the others, since the waves will be
superimposed on each other.

The arrangement of coil set 79 and pistons 82
shown in Figure 12 results in an axial movement of said
piston. However, it can advantageous to turn the
coil/piston assembly through 90° so as to obtain a radial
movement of the piston.

Still another alternative for the vibrator is shown in Figure 13. The coupling scheme shows the hydraulically operated connector 35, attached to the end of the production string 32 with its insulated packer 23,

5 below the enlarged area 70. Below the coupling 69 is a void space 77, intended for the electrical switches of the vibrator. The vibrator consists of a series of coils 87 wound around a core of iron sheets 88 so that each magnetic pole in the ends of the coils is identical. This means

10 that the north pole of a coil is turned to the north pole of the north, and the south pole of that is turned to the south pole of the following coil. The cores of rolled iron 88 are formed so that each iron end of the coil is the same in each coil. The set of coils, in one of the possible

15 arrangements, is placed in a square hollow tube 89 of elastic magnetic material, like a steel spring, with a space for the coils 87 and the rolled iron core 88. In another arrangement, the tube 90 is circular and of the same type of material, and therefore the ends of the rolled

20 cores facing into the tube are circular. It must be understood that it is possible to utilize rolled tubes where the internal tube is made of an elastic magnetic material and the external tube is made, for instance, of stainless steel.

25 The operation of this vibrator is described as follows. When the electrical current passes through the coils 87 and then the connector 35 and into the producing formation, an oscillating magnetic flux B is generated at the coils, which changes in direction with the frequency of

30 the current. Due to the fact that the magnetic poles in the coils face each other, a closed magnetic circuit will be obtained for each coil, as shown in Figure 12. Since the oscillating magnetic flux will attract the tubes, it will vibrate at twice the frequency of the main source.

35 Since the attracting is stronger between the coils, the assembly will transmit a number of wave trains larger than

the length of the vibrator. Each wave pulse will have, in
its vertical projection, the format shown in Figure 13, and
in its horizontal projection, the format illustrated in
details A and B of Figure 13. The advantages of this are
5   the same as indicated for the movement of the tube, and
therefore of the casing, as mentioned for the expansion
element of the vertical vibrator of Figure 7. It must be
pointed out that it is possible to attract the casing
directly without using the expansion tubes 89 or the non-
10 magnetic tubes as protectors of the coils.

To reach the low frequency, this may be
achieved as for the vibrator of Figure 7 or as shown in the
scheme of Figure 14.

The direction of the main current which is
15 heating the producing formation, represented here as
impedance Rj, may be changed by means of a thyristor
adjusted at a frequency to pass through the vibrator and
then activate the coils LVIBR.

With the use of rolled tubes, in which the
20 external tube is non-magnetic, the magnetic tube serving as
armature will reach the external tube as it returns, after
the magnetic force ceases, and will then generate a sharp
pulse as that described for the vibrator of Figure 12.

In addition, it has been verified that the
25 interaction of the electrical and acoustic stimulation
results in an effect much stronger than the utilization of
either of those stimulations separately.

The distribution of heat and energy in the
reservoir by the electricity and by the sonic waves may be
30 calculated in the same way as the heat effectively released
by friction. The friction caused by sonic stimulation is
created by the oscillation of the fluid droplets but, due
to the electricity, it is generated by the molecular
movement. The total energy input is thus limited by the
35 cooling capacity of the oil produced. The calculation for
this is simple:

$$Q = M c (t_2 - t_1) \quad \text{(kJ/time unit)}$$

where: M = mass of petroleum for each time unit (kg/h)

c = specific heat of petroleum (kJ/kg°C)

t_2 = well temperature

5   t_1 = average reservoir temperature

It should be noted that any of those vibrators can be used for well- or any other logging and/or stimulation known in the art, such as coalescing, vibro-drilling, de-icing of soil, fracturing etc.

C L A I M S

1. A process for increasing the recovery of
petroleum from petroleum reservoirs, wherein the producing
5 formation is simultaneously subject to electrical and
vibratory stimulation, in which the electrical current is
supplied to the reservoir by means of an electric conductor
installed in an annular gap between a production string and
a well casing; wherein part of the energy is utilized to
10 operate a vibrator attached to the end of the production
string, the electrical connection being obtained by means
of hydraulically driven connectors located at the vibrator
and attached to the uncovered end of the electric cable;
wherein said connectors conduct the electric current to the
15 well casing which penetrates the producing formation at a
point located above an isolation bridge; wherein part of
the well casing is located above the producing formation
and there is a cut at a certain height above said producing
formation defining a cavity which is filled with an
20 electrically insulating material.

2. A process according to claim 1, wherein the
current is supplied to the reservoir by means of the
production string which is centralized inside the casing by
means of electrically insulating centralizers.

25 3. A process according to claim 1, wherein the
current is supplied to the reservoir by means of an
isolated casing.

4. A process according to any of the preceding
claims, wherein the vibrator is of mechanical type which
30 reciprocates vertically, energized by current impulses
supplied to the reservoir as alternating current, as direct
current pulses tapped from the main power source, or as
pulses supplied from capacitors, transformers or magnetic
coils, all energized from the main power source.

35 5. A process according to claim 4, wherein the
energy of the vertical displacement may be oriented at

approximately 90°, and may be amplified, hitting the different expansion elements, such as a bar having attached thereto v-shaped moving bodies located in several manners so that, as the bar is displaced, each second body moves
5 against the other and compresses the liquid between the bodies, generating pressure pulses capable of making the casing oscillate in several ways in accordance with the acoustic characteristics of the reservoir.

6. A process according to claim 4, wherein the
10 vibrator may be oriented at nearly 90° and have its action amplified by displacement of a piston into a liquid contained in expansion tubes of different cross-sections, so that the various sound waves may make the casing oscillate in different ways in accordance with the acoustic
15 characteristics of the reservoir.

7. A process according to claim 4, 5 or 6, wherein the energy of the vertical displacement of the vibrator may impinge on any expansion devices, which may alter and/or amplify the course of the original vertical displacement.

20 8. A process according to claim 1, 2 or 3, wherein the vibrator is of the electromechanical type which reciprocates horizontally, energized by current pulses originating from the alternating current fed to the reservoir itself, or by pulses of direct current tapped
25 directly from the main power source, or by pulses supplied by capacitors, transformers or magnetic coils, all of them energised from the main power source.

9. A process according to claim 8, wherein the pulse of the vibrator is generated through the momentum resulting
30 from the superimposition of electrical and magnetic fields; wherein the magnetic field is generated by a coil wound around a rolled core; and wherein the expansion elements which conduct the current are a corrugated tube in stainless steel and filled with a conducting liquid, or a
35 hose made of silicone and filled with a conducting liquid, or a steel tube divided into current-conducting elements

united by a support means attached thereto.

10. A process according to claim 9, wherein said support means are a silicone hose or a corrugated steel tube.

5   11. A process according to claim 8, 9 or 10, wherein the pulse of the vibrator is activated by the attraction of a special expansion tube towards the steel casing, due to a magnetic field generated from a coil wound around a rolled core, so that said steel casing or the expansion tube acts 10 as if it were the wave-transmitting element.

12. A process according to claim 8, 9 or 10 wherein the pulse of the vibrator is achieved by hammering pairs of bars located in the center of magnetic coils against radially oriented bodies by means of magnetic forces, so 15 that the radially oriented bodies amplify the force in the hitting and orient it at 90° by hitting an expansion tube located externally to the coils, so that the expansion tube vibrates as if it were the wave transmitting element itself.

13. A process for increasing the recovery of 20 petroleum from a petroleum reservoir, substantially as hereinbefore described with reference to the accompanying drawings.

14. Apparatus for increasing the recovery of petroleum from petroleum reservoirs, comprising a 25 mechanical vibrator energized by current impulses supplied to the petroleum reservoir itself from the main power source; wherein said vibrator receives energy causing a displacement which can be oriented approximately at 90° and/or amplify the course of the original displacement by 30 hitting different kinds of expansion devices which may make the casing oscillate in different ways in accordance with the acoustic characteristics of the reservoir.

15. Apparatus according to claim 12, wherein the vibrators can oscillate vertically and horizontally.

35   16. Apparatus for increasing the recovery of petroleum from petroleum reservoirs, constructed and

adapted to operate substantially as hereinbefore described
with reference to, and as illustrated in, the accompanying
drawings.

Patents Act 1977
Examiner's report to the Comptroller under Section 17 (The Search Report)

Relevant Technical fields	**Application number** GB 9213976.5

Relevant Technical fields	**Search Examiner**
(i) UK Cl (Edition K) E1F (FME) (ii) Int Cl (Edition 5) E21B	D B PEPPER
Databases (see over) (i) UK Patent Office (ii) ON-LINE DATA BASE WPI	**Date of Search** 19 AUGUST 1992

Documents considered relevant following a search in respect of claims 1 TO 13

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A	US 4884634 (ELLINGSEN)	1

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

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